Improved Methods for Correlating Turbidity and Suspended Solids for Monitoring

PURPOSE: This technical note describes techniques normally used to measure turbidity and suspended solids in waters, how the two parameters relate to each other and to various environmental impacts, and why one cannot be routinely substituted for the other. It further outlines a technique whereby simple and quick turbidity measurements can be used as an operational aid in monitoring dredging and dredged material disposal operations as an adjunct to more costly and time-consuming suspended solids measurements.

BACKGROUND: Resuspension or discharge of suspended solids during dredging and disposal of sediments can cause significant environmental impacts. Therefore, water quality regulatory agencies often impose permit conditions limiting the concentration of suspended solids that can be present at specified locations near the operating dredge, point of open-water disposal, or point of effluent discharge from a confined disposal facility (CDF). Suspended solids concentrations cannot be determined easily and quickly in the field, however, and transportation to a laboratory and analysis are time-consuming and costly. Therefore, suspended solids measurements cannot be easily used to detect and correct short-term problems or permit violations.

Because of these problems, turbidity measurements are often substituted for suspended solids. Turbidity is easy to measure quickly, but there is no universal relationship between it and suspended solids, nor among turbidity measurements made on different water-sediment suspensions, nor even among turbidity measurements made on the same suspension with different instruments. In addition, turbidity does not correlate well with many categories of environmental impact. However, turbidity can be used to indicate suspended solids concentration on a site-specific basis, if certain specific techniques are used.

DEFINITIONS, UNITS, AND MEASUREMENT METHODS: The term total suspended solids (TSS), sometimes referred to simply as suspended solids (SS), encompasses both inorganic solids such as clay, silt, and sand, and organic solids such as algae and detritus. It is a measure of the dry weight of suspended solids per unit volume of water, and is reported in milligrams of solids per liter (mg/L) of water. The analysis is performed in four specific steps (American Public Health Association (APHA) et al. 1992), summarized as follows:

1. Dry a glass fiber filter in an aluminum foil dish to constant weight at 103 °C, cool it in a desiccator, and weigh it and the dish (all weights typically measured to the nearest 0.1 mg).

2. Filter a known volume of sample water through the filter.

3. Place the wet filter and its trapped solids in the dish again, dry it in the oven to constant weight at 103 °C again, and weigh it again.

4. Subtract the first weight from the second weight and divide by the volume of sample in liters to get the suspended solids in milligrams per liter.

Although popularly called suspended solids, this method is more accurately called nonfilterable solids (or residue), because the size of separation (about 0.45 µm) is not the same as the boundary between suspended and dissolved solids, which varies among molecules but is generally around 0.1 µm.

Turbidity is an optical property of water that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. It is caused by the molecules of water itself, dissolved substances, and organic and inorganic suspended matter. Devices commonly used to measure turbidity include the Jackson candle turbidimeter, absorptimeters, transmissometers, and nephelometers (McCarthy, Pyle, and Griffin 1974). All but the nephelometer measure the effects of both absorption and scattering of light. The nephelometer measures scattered light only, and is the most commonly used device in colloidal chemistry, potable water treatment, and water quality management.

Nephelometers use a device such as a photomultiplier tube or silicon photodiode to measure light that has been scattered at a specific angle, usually 90 deg, from the main light path. The light source is usually a tungsten filament lamp or a light-emitting diode, and the light path is designed to minimize stray light falling on the detector. Thus, a zero signal means no light scattered at 90 deg from the main light path and implies no turbidity.

The ability of a particle to scatter light depends on the size, shape, and relative refractive index of the particle and on the wavelength of the light (Lillycrop, Howell, and White 1996). The reading on the instrument depends on many design parameters, including the light source, detector, electrical circuit, sample container, and optical arrangement. Therefore, two samples with equal suspended solids concentrations but different size distributions of particles will produce very different turbidity readings on the same nephelometer; and two different nephelometers may produce different turbidity readings on the same sample, even if they were calibrated on the same standard (Vanous 1978; APHA et al. 1992; Hach 1972). Although the original Jackson candle turbidimeter was standardized with a specific fine silica suspension in which one Jackson Turbidity Unit (JTU) equaled 1.0 mg/L of TSS, modern turbidimeters are no longer standardized against the Jackson candle, and the term JTU is no longer used.

Modern turbidimeters are standardized against a formazin suspension with a value of 40 Nephelometric Turbidity Units (NTU). The standards should be prepared according to *Standard Methods* (APHA et al. 1992). The 400-NTU stock suspension should be prepared monthly, and the 40-NTU standard turbidity suspension should be prepared daily. Experience shows that this turbidity can be repeatedly prepared within an accuracy of ±1 percent (Hach 1972). The formazin turbidity standard is assigned a value of 40 NTU and can be diluted to any desired value. It reads approximately 40 JTU on the Jackson candle turbidimeter, but is not exact. The Jackson candle turbidimeter is no longer an accepted standard method (APHA et al. 1992).

The Secchi disk is a white disk, 20 to 30 cm in diameter, commonly used by oceanographers and limnologists to indicate water clarity (the opposite of turbidity) instead of measuring turbidity. The disk is lowered into the water to the depth where the sharp outline disappears into a formless glow. The depth is then recorded. This method is quick, easy, and cheap, but is somewhat subjective and

imprecise. It varies from a meter or less in highly turbid waters to 30 to 40 m in clear ocean water. It has limited use in monitoring dredging operations.

Numerous authors have published data that show good correlations between TSS and one or more types of more easily performed turbidity measurements, or among various types of turbidity and absorbance measurements, *at a specific site* (Jones and Wills 1956; Postma 1961; McCarthy, Pyle, and Griffin 1974; Duchrow and Everhart 1971; Ohira, Nikaido, and Takagi 1987; JBF Scientific Corporation 1978; Austin 1974). Austin (1974) found that Secchi disk visibility is inversely proportional to the total surface area of the particles in the water, instead of their weight, but that organic particles, such as algae, scatter light less than inorganic particles of the same size. Jones and Wills (1956) found a linear relationship between TSS concentration C and the light attenuation coefficient α for artificial suspensions, but not for sea water, except at TSS < 10 mg/L. They found a linear relationship between α and $1/D$ (where D is the depth of Secchi disk visibility) for sea water up to α of 3, TSS of 12 mg/L, and D down to 2 m, which implies a linear relationship between C and $1/D$, but only over a limited range. However, all of those relationships are specific to a particular place, suspension, and time.

The theoretical considerations mentioned earlier prevent any simple, universal relationship between TSS and turbidity from ever being developed, because they measure different things, and their values are functions of different variables (Lillycrop, Howell, and White 1996). TSS depends on the total weight of particles in suspension, and is a direct function of number, size, and specific gravity of the particles, while turbidity is a direct function of the number, surface area, and refractive index of the particles, but is an inverse function of their size (for constant TSS).

STANDARDS AND COMMON PRACTICES: The measurement of turbidity is most common in the water treatment industry (drinking water), because consumers want clear water. Turbidity standards (0.5 NTU) and goals (0.1 NTU) are primarily for aesthetic reasons, although NTU values above 1.0 indicate that enough solids may be present to harbor bacteria and impair disinfection.

The primary reason for wanting to use turbidity measurements instead of suspended solids is that turbidity measurements are quick. Nephelometric turbidity readings can be done in a matter of minutes. On the other hand, taking a sample, transporting it to the laboratory, filtering it, drying it, weighing it, and calculating the TSS value can take from 6 to 24 hours. In the meantime, the TSS of the discharge or water body of interest will have changed.

Most discharge or monitoring permits connected with dredging operations are based on TSS rather than turbidity, because TSS correlates well with environmental impact and is at least roughly comparable from site to site and sediment to sediment. A TSS of 100 mg/L at one site would have approximately the same potential for impact as a TSS of 100 mg/L at another site with very different sediment size characteristics, because it indicates that approximately the same volume of material is present. However, a turbidity of 50 NTU with one suspension is not comparable in TSS or potential for environmental impact to another suspension with a turbidity of 50 NTU, but with a different size distribution of particles. This comparison assumes that, in either case, no toxic or otherwise hazardous chemical constituents are adsorbed on the sediment particles. In fact, if such chemicals are present, they tend to adsorb more on fine particles with high specific surfaces.

Some states use a maximum turbidity standard, commonly 25 or 50 NTU, and some states allow an arbitrary increment, commonly 50 NTU, above background (Lillycrop, Howell, and White 1996). However, McCarthy, Pyle, and Griffin (1974) argue that this is not logical, because it would be too restrictive in some cases and too lenient in others. In waters of nominal turbidity (10-15 NTU), an increase of 50 NTU would allow a threefold to fivefold increase over natural levels. In extremely clear waters (1-3 NTU), the increase could be up to two orders of magnitude. On the other hand, in very turbid natural waters (100-1,000 NTU), an increment of 50 NTU may be extremely restrictive. They argue for a turbidity limit of an increase of a certain percentage of normal background, if turbidity is to be used as the standard, for convenience.

In general, waters over a sandy or gravelly substrate have low turbidity under normal conditions, because the large particles do not stay in suspension very long. Consequently, dredging of coarse substrates, which resuspends large amounts of solids, might not violate turbidity standards. Conversely, dredging very fine sediments, which are usually overlaid by turbid waters because the substrate is easily suspended and settles slowly, may cause a large increase in turbidity. Therefore, from both an engineering and a legal standpoint, TSS is preferable as the variable to be measured to enable resultant data to be interpreted in a meaningful manner.

However, because of the previously mentioned difficulties with using TSS in routine compliance monitoring and the convenience of turbidity monitoring, many authorities are using turbidity. Therefore, it is important that turbidity standards be set and used in a logical manner that reflects reality, protects the environment, and facilitates dredging.

USE OF TURBIDITY-TSS RELATIONSHIPS IN DREDGING: Earhart (1984) described a procedure designed to ensure compliance of three effluents from diked CDFs with a TSS standard of 400 mg/L. The U.S. Army Engineer District, Baltimore, was concerned about potential violations of this restrictive standard. The District was also concerned about the legal and economic ramifications of requiring a dredging contractor to cease operations because of a potential violation of the TSS standard that could not be verified until 24-48 hours later, when the results of a gravimetric analysis became available. If the analysis did not reveal a permit violation, the recurring damage claims of the contractor based on unnecessary delay could have been significant.

Earhart (1984) reported that samples of sediments and waters from the three dredging sites were taken and mixed to form suspensions, from which samples were taken for gravimetric analysis for TSS and turbidity measurement by a Model 16800 Hach Portable Turbidimeter. The suspensions were then diluted back to the original volume with ambient site water and remixed, and the procedure was repeated. In this way a series of increasingly dilute samples was analyzed for TSS and turbidity, and the pairs of results were plotted to form a correlation curve. About 50 pairs of results were plotted, so the 95 percent confidence limits were reasonably narrow. The correlation curves were used to determine the turbidity at which the TSS would be 400 mg/L, indicating a violation. This turbidity value was then routinely compared with the measured turbidity of the effluent from the containment area as an operating control measure by an onsite inspector.

In order to check the accuracy of the control method, several samples of effluent from the containment area were sampled for both TSS and turbidity, and the results were compared to the laboratory correlation curve derived from in situ samples. The samples used for comparative

analysis contained both larger and smaller particles, and the larger particles were resuspended each time the diluted samples were remixed. A larger particle contributes much more to the TSS than a small particle because of its much larger volume and weight, but does not contribute much more to the turbidity than a smaller particle.

In the effluent from the containment area, larger particles are not usually present, having settled in the containment area. Only the smallest particles remain. The removal of larger particles reduces the TSS, based on the mass of the particles, which is a function of the particle diameter cubed, much more than it reduces the turbidity, based on the number of particles or their surface area, which is a function of the diameter squared.

Based on this rationale and an analysis of the physics of light scattering and turbidity, one concludes that any samples used to produce a correlation curve between TSS and turbidity must be suspension-specific, not just site-specific. The sample must approximate the suspension to be represented in the size, number, shape, and type of particles. If the suspension to be represented is the effluent from a containment area, in which a sediment suspension is modified by settling, the best way to approximate the effluent suspension is by subjecting sediment samples to a comparable period of settling. A recommended procedure for conducting such a test is described in the next section.

RECOMMENDED PROCEDURES: There are three general situations for which one might wish to use a TSS-turbidity correlation curve as an aid in routine monitoring of a dredging operation for which TSS standards or operating guidelines have been set:

1. Monitoring resuspension of solids in the immediate vicinity of the dredge.

2. Monitoring for TSS in the effluent discharge from a CDF containment area or sedimentation pond.

3. Monitoring for TSS during open-water dredged material placement.

Solids resuspension near dredge. For this case, in the immediate vicinity of the dredge, most solids, large and small, will be present, because they will be continuously replenished by the action of the dredge. However, these high TSS concentrations usually do not persist more than about 20-50 m from the dredge, if that far (LaSalle et al. 1991; McLellan et al. 1989). Therefore, the TSS and turbidity measurements should be made on dilutions of the whole sediment samples, similar to the method of Earhart (1984). The method used by Earhart (1984) is summarized as follows:

1. Prepare a 1-L mixture of wet sediment and site water by adding 10 g of wet sediment to a 1-L graduated cylinder, and then filling the cylinder with site water.

2. After agitating the mixture, extract 20 mL for TSS measurement and 40 mL for turbidity measurement with a pipette.

3. Add 60 mL of site water to the cylinder to increase the volume of water to 1 L. Repeat the extraction for TSS and turbidity measurement.

4. Repeat the process, developing a series of approximately 50 serial dilutions.

Containment area effluent. In this case, the larger, heavier solids will settle near the inflow point for the CDF and only finer particles will be present in the effluent. The permit limitation will frequently be on the TSS at the limit of a mixing zone some distance from the effluent weir discharge. A laboratory settling column and test procedure has been developed for prediction of the effluent TSS (Montgomery 1978; Montgomery, Thackston, and Parker 1983; Thackston and Palermo 1988; Palermo and Thackston 1988a,b,c; Headquarters U.S. Army Corps of Engineers (HQUSACE) 1987; and U.S. Environmental Protection Agency (EPA)/U.S. Army Corps of Engineers (USACE) 1998). In this procedure, the sediments are mixed with water from the site to a slurry concentration approximating the dredge discharge concentration, pumped into the 20-cm (8-in.) by 180-cm (6-ft) column, and allowed to settle. This settling column test is also routinely used, along with the modified elutriate test described by Palermo and Thackston (1988b,c), to predict the concentration of contaminants in the effluent from diked disposal areas.

The same laboratory settling column test can be used to develop the data for a correlation of TSS versus turbidity. The column test procedure for CDF effluent quality evaluation requires that samples for TSS be taken from the column from a series of sampling ports along the length of the column (HQUSACE 1987; EPA/USACE 1998). Therefore, the data needed for the correlation curve can be produced by simply performing a turbidity analysis on the samples taken for TSS analysis during the column test. The samples of most importance will be those taken at times near the expected average hydraulic retention time of the containment area, when the TSS and turbidity are reduced to values approximating those in the effluent from the containment area.

If this settling column is not available, other types of settling containers may be substituted, such as large graduated cylinders, but accuracy may be compromised. The most important factors are the column diameter, which should be at least 15 cm (6 in.), and preferably 20 cm (8 in.), in order to avoid wall effects, and sampling just below the surface in a manner that does not cause mixing.

The recommended procedure for producing a TSS-turbidity correlation curve would then consist of the following steps:

1. As soon as the slurry has started to settle, begin taking samples from the uppermost column sampling ports or from just below the water surface in the settling column. A suggested sample volume is 50 mL.

2. Continue to take additional samples from the uppermost sampling ports remaining below the water surface or from just below the water surface as the test progresses. It is not necessary to maintain a precise or uniform interval for sampling, but a larger number of samples should be taken at first with an increasing interval as the test progresses. The optimum sampling intervals will depend on the settling behavior of the specific sediment. At least 20, and preferably 50, samples should be taken within the first day or two of the test, and samples should be taken until the supernatant becomes clear and the TSS and turbidity have obviously dropped well below the limits set in the permit. An initial interval of 30 minutes to 1 hour is recommended for the first 8 to 16 hours of the test, with increasing intervals of 2 hours, 4 hours, etc., as the test progresses.

3. Analyze each sample for TSS and turbidity.

4. Plot TSS as the y-axis versus turbidity as the x-axis.

5. If the plot reveals a relationship that looks linear, calculate the equation for the line of best fit, of the form $y = ax + b$ and plot it on the graph with the data points, along with the 95 percent confidence limits. If it is not linear, use a nonlinear curve-fitting program.

Open-water disposal. The TSS-turbidity correlation curve for open-water disposal should be produced in the same manner as that for the effluent from a diked containment area. In this case, the larger, heavier solids will begin to settle to the bottom immediately upon exiting from the dredge discharge pipe, hopper, or barge usually in a more or less well-defined plume. The permit limitation will frequently be on the TSS at the limit of a mixing zone at or near the surface a specified distance from the discharge. Only those solids that have not settled in the time it takes for water to flow from the discharge point to the measurement point at the prevailing surface velocity will be present. The best way to obtain a representative sample of solids that are likely to be in suspension at that point is with a laboratory column settling test as described previously.

Use of correlation curve for field monitoring. When the dredging or disposal operation is in progress, samples of water can be taken at the points of compliance specified in the permit and quickly analyzed for turbidity, even on the sampling boat. TSS can then be estimated directly from the correlation curve.

The curve produced by this procedure can be used in the beginning phases of the operation to monitor compliance with TSS standards on a routine basis, and the operation can be stopped or modified if the turbidity values indicate a TSS standard violation. Some samples will have to be analyzed for TSS in addition to turbidity to check for actual compliance with the standards, in addition to estimated compliance. Any samples suggesting noncompliance must be checked. These samples should also be analyzed for turbidity and the data plotted on the laboratory-produced TSS-turbidity correlation curve. When sufficient field data are available, the correlation curve should, if necessary, be recalibrated including the new field data. The recalibrated curve can then be used for the remainder of the project with even greater confidence.

EXAMPLE: A laboratory column settling test was performed to obtain data for the design of a dredged material containment area for sediments from Mobile Harbor. Both TSS and turbidity were measured on the samples taken from the supernatant. The circles plotted in Figure 1 represent these data, and the solid line is the linear regression line of best fit and represents the laboratory-developed correlation curve.

When the dredging project was underway, effluent samples were also analyzed for TSS and turbidity. These data are plotted as triangles in Figure 1, and the dotted line represents the linear line of best fit.

Using the laboratory-derived solid line, a turbidity of 40 NTU is estimated to represent a TSS of about 70 mg/L with a range of about 55 to 90 mg/L. The dotted line representing the field data indicates that a turbidity of 40 NTU represents a TSS of about 52 mg/L with a range of about 25 to 60 mg/L. Although there are obvious differences in the two sets of data, the laboratory and field correlations are in closer agreement than similar data sets produced by Earhart by analyzing whole
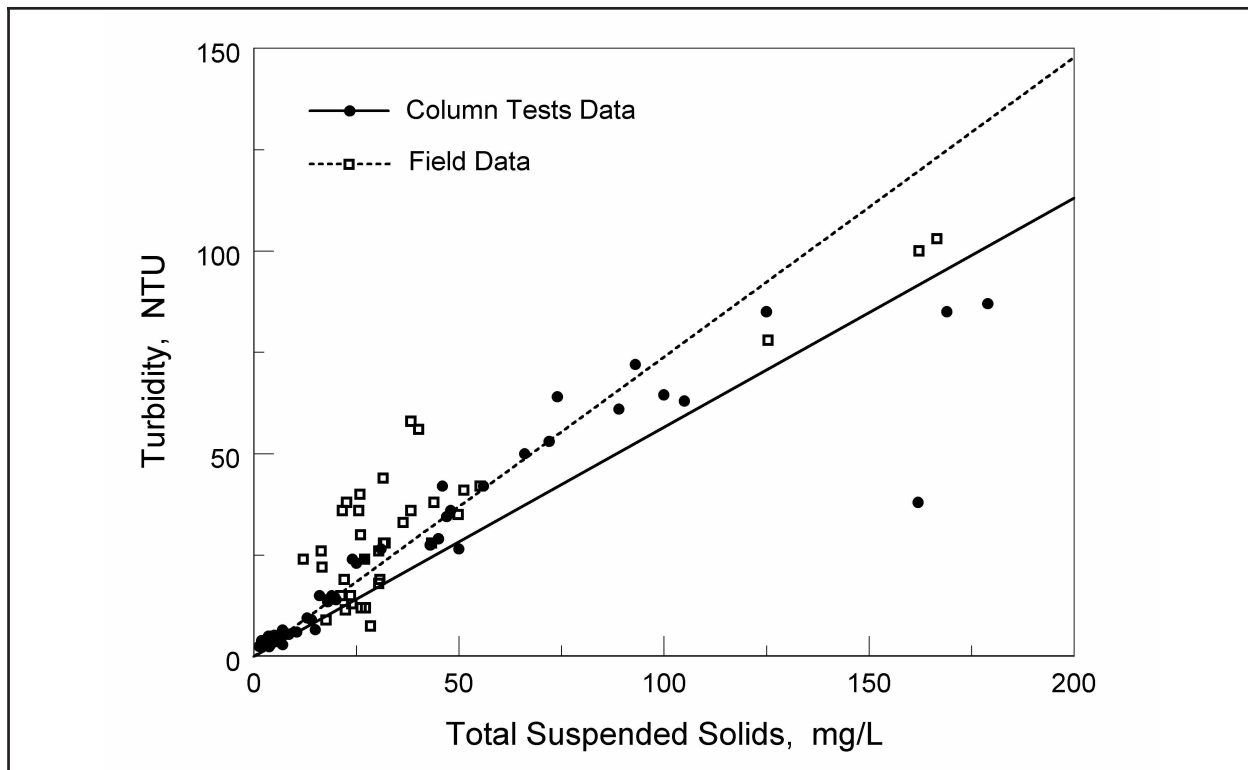
Figure 1.   Comparison of laboratory column and field data and linear regression lines for Mobile Bay
sediment

sediment samples. This indicates that the laboratory data curve can be used as a routine operating aid until sufficient field data are produced to construct a better correlation curve based on field data alone.

In this situation, the TSS predicted by the column test was slightly higher than the actual TSS measured in the field for identical turbidities, 70 mg/L versus 52 mg/L in the field. Thus, it is a conservative predictor, slightly more protective of the environment, which is appropriate. However, it is not so overly conservative as to be overly restrictive on the dredging contractor.

The differences in the two sets of data, in their lines of best fit, and in the scatter in the data do emphasize the importance of verifying the accuracy of the laboratory predictions as soon as possible after dredging starts. Some projects produce better correlations than others. The Mobile Bay data are fairly typical. An example of a good correlation is shown in Figure 2. As soon as the project is underway and operating conditions have begun to stabilize, it is critical that field sampling for both turbidity and TSS begin. A monitoring curve based on or incorporating actual field data should be produced as soon as possible after dredging starts.

The lines of best fit in Figure 1 are the best fit linear lines, but a cursory examination of the data reveals that the data do not form a linear pattern over the whole range, but only below approximately 50 mg/L TSS. Correlation curves in the form of exponential equations would fit the data much better over the whole range, but linear lines were used in this example to illustrate the simplicity of the technique. Alternatively, only the data below a given value of TSS could be used to produce
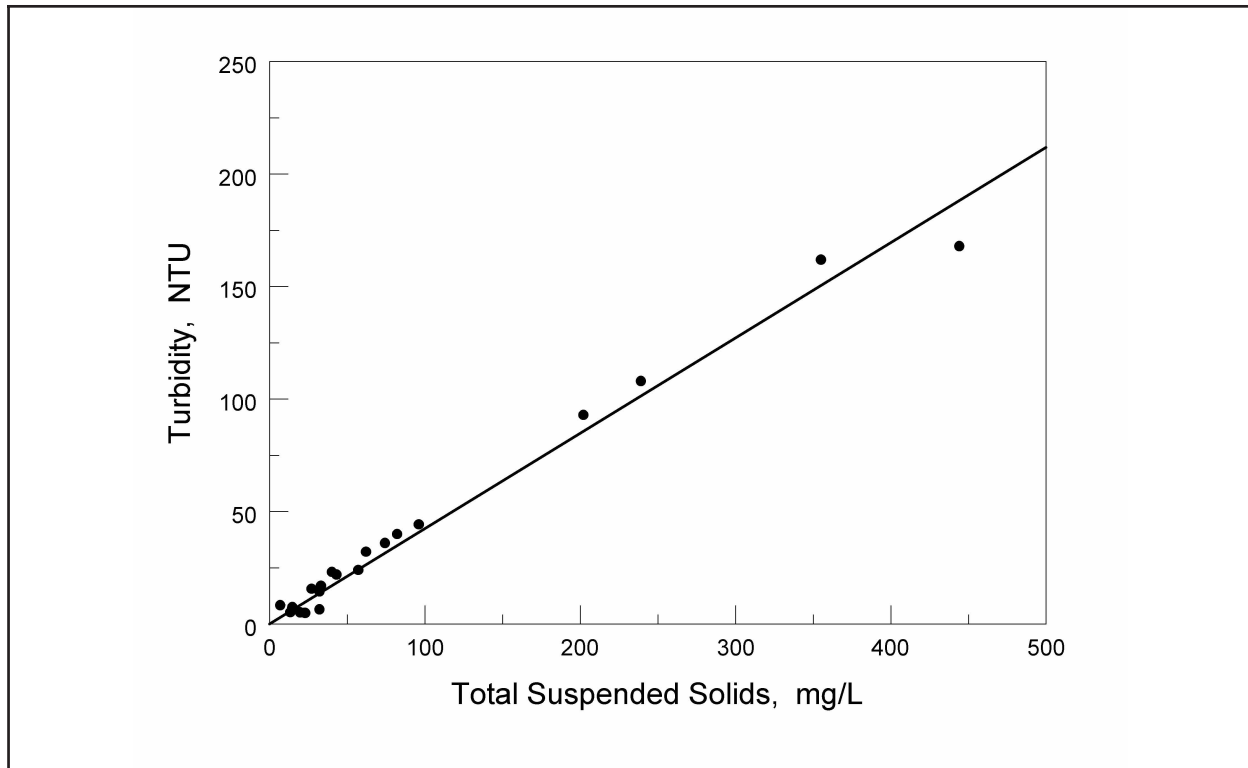
Figure 2.   Laboratory column data showing relationship of turbidity and TSS for Middle Ground Island
sediment

the correlation curve, where the upper bound of TSS data used is approximately the maximum TSS that will be allowed in the discharge.

Another potential problem is the use of a laboratory curve derived from one location for a different location. This should be strictly avoided. Even sediments from different reaches of the same channel can have different physical characteristics and different turbidity-TSS correlation curves. If the physical characteristics of the sediments change along a project, different laboratory correlation curves should be derived and later field-adjusted.

This situation is illustrated in Figure 3, which shows laboratory correlation curves on sediments from five locations in addition to Mobile Harbor. Even the three reaches of the Calcasieu River produce different curves. For a turbidity of 50 NTU, the curve from reach 1 would predict a TSS of 300 mg/L, that from reach 2 would predict a TSS of 250 mg/L, and that from reach 3 would predict a TSS of 225 mg/L.

If these procedures and cautions are used, the use of turbidity as a surrogate for TSS can be a useful aid to monitoring dredging projects. Because a relatively large number of samples can be checked routinely and quickly, arbitrary and costly delays or shutdowns can be avoided.

CONCLUSIONS: Turbidity and suspended solids are common parameters of concern of regulating agencies and are often included in environmental monitoring plans for dredging operations, open-water disposal, and confined disposal effluent discharges. Measurement of suspended solids takes several hours and is impractical, when conditions change rapidly, for use as a control strategy.
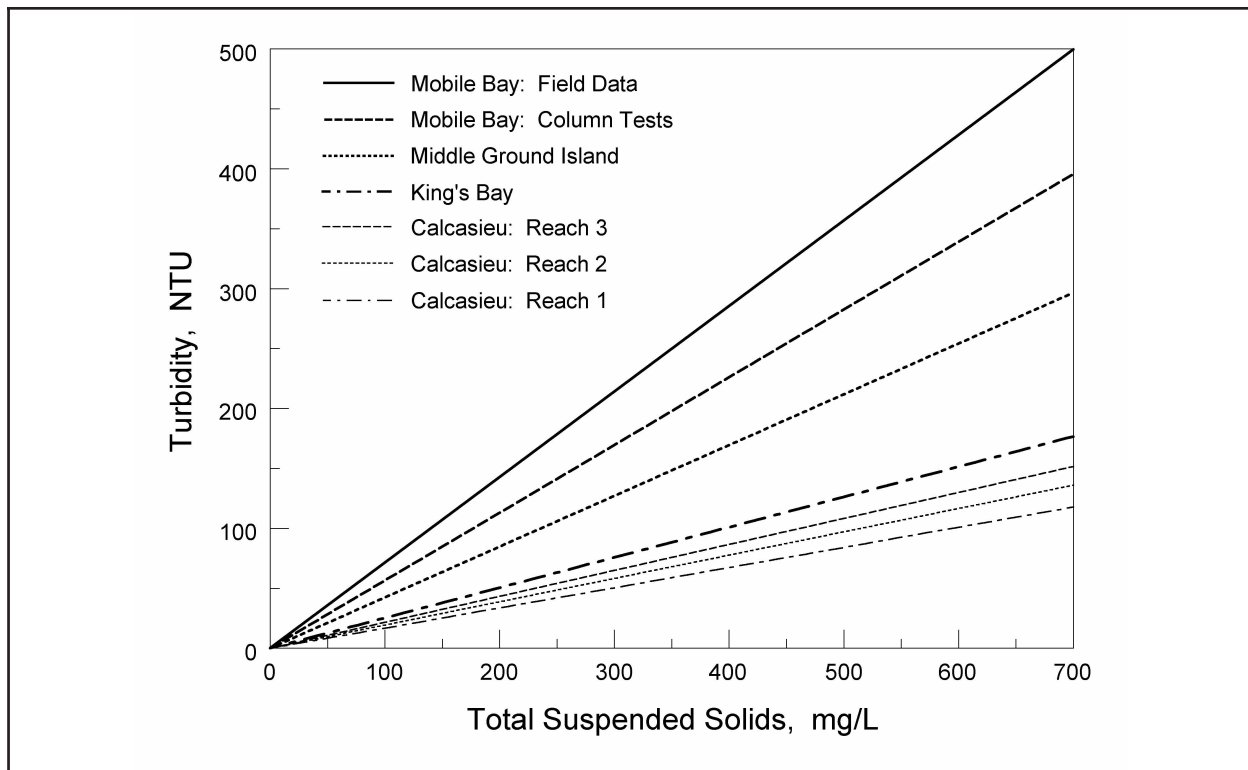
Figure 3.   Combined regression plots, showing differences among lines for different sediments

Turbidity can be measured in real time, but does not necessarily correlate well with potential environmental impact. There is no universal correlation of turbidity and suspended solids, but sediment-specific correlations are useful as a real-time indicator of suspended solids. Such correlations have often been developed in the laboratory using whole sediment samples. However, correlations based on whole sediment samples can be inaccurate for dredging applications where only specific fractions of a sediment are involved, such as for CDF effluent monitoring. This technical note describes an improved method for developing correlations based on use of a column settling test in which only the finer fractions of sediment are considered. This approach eliminates potential inaccuracies in developing the correlations using whole sediment samples. Field data indicate the improved method is practical and accurate.

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